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THESIS

MAXIMIZATION OF THE CAPACITY OF THE MOST
SURVIVABLE CONNECTIONS IN A NETWORK

by

Richard V. Stockton

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Thesis Advisor: Jack W. LaPatra

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Maximization of the Capacity of the Most Survivable Connections in a Network

by

Richard V. Stockton
Lieutenant, United States Navy
B.B.A., University of Oklahoma, 1979

Submitted in partial fulfillment of the requirements for the degree of

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ABSTRACT

The survivability of a communications network is considered to be a function of the number of independent parallel paths between a source and destination node. A methodology is developed to determine the connectivity of a network and then the number of independent parallel paths are determined by restricting the connectivity solution set. The capacity of the parallel paths are then maximized given that the links are not characterized by uniform capacities.

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I. INTRODUCTION

The United States is becoming increasingly dependent on telecommunications to maintain societal structure. Today, the use of communication and computer networks has attained a level which affects all lives. The loss of these networks would have a monumental effect on the everyday lives of virtually every person in the U.S. and even the world.

The networks of today provide the ability to control many distributed systems. Banking institutions use computer networks to handle enormous interbank transactions as well as to control their hundreds or even thousands of remote teller machines. Design engineers, physically separated, use computer networks to allow simultaneous development of similar concepts. The military uses communication networks to provide the command and control necessary for its forces in peacetime as well as war. The government would depend on available communication assets to coordinate rescue and relief efforts after a major catastrophe.

Much effort has been expended attempting to determine the effects of nuclear blasts upon specific existing telecommunication networks and the post attack emergency communication networks which could be reconstructed [Refs. 1,2]. An even greater volume of research has been completed which

addresses random failures in networks. The analysis of random failures on communication networks is mature and many theories and mathematical models have been advanced.

Apparently, little research has been completed in assessing the consequences of malicious attack designed to maximize disruption of telecommunication services [Ref. 3: p. 1668]. The logical reason for this lack of research is the high cost associated with protecting current communication systems from malicious attack. The high cost of protection added to the low probability of malicious attack leaves the telecommunications industry little economic incentive to research this area. Thus a few agencies of the government with direct interest in the establishment of emergency communication networks are left to thoroughly research this area, a task which has been overlooked in the past.

In time of major catastrophes it is essential for the government to have access to adequate communication systems to allow the continuance of societal functions. After an earthquake, hurricane, terrorist attack, or a nuclear war the telecommunications manager must survey the surviving communication assets and construct the most effective emergency network possible. It is imperative for the communications manager to have a measure of survivability which may be used to assess the affects of damage or destruction on

the emergency telecommunications network. This measure could be a decision aid to the manager to allow quick judgements to be made on the optimal configuration for the available assets.

Any measure of survivability developed should be useful in assessing the vulnerability of existing networks and may serve to establish technical priorities for enhancing existing network survivability. The measure should address important elements of survivability such as capacity, connectivity, and others. [Ref. 4]

The research for this thesis will be aimed at answering the following questions:

1. Can a methodology be developed to limit the effects of damage or destruction on emergency telecommunications networks?

2. If a methodology can be developed, may this method serve to establish technical priorities for enhancing network survivability?

3. How may this methodology be employed to reconstruct telecommunications capabilities after damage?

II. BACKGROUND

A. NATIONAL COMMUNICATIONS SYSTEM

1. Mission

In 1962 the United States faced the threat of offensive nuclear missiles being placed in Cuba, only 90 miles from Florida. In the ensuing tense days following detection of the missile sites, President Kennedy encountered difficulties in mobilizing the national resources of the United States due to the uncoordinated and poorly managed structure of the national communications systems. The National Communications System(NCS) was therefore established in 1963 to provide the necessary communications for the Federal Government to perform its governing functions under all conditions, normal everyday working conditions up to nuclear war [Ref. 5: p. 20]. The Mission on the NCS remains virtually identical today [Ref. 6: p. X]. Since its inception the NCS has worked to increase emergency preparedness of the national telecommunication systems, both within and out of the federal government.

2. Assets

The National Communications System may count many publicly owned communications assets which are leased to the government. During national emergencies the most essential

communication assets are considered to be those systems capable of carrying voice or moderate data rate information [Ref. 7: p. 1]. These systems are considered essential to allow adequate emergency preparations and post catastrophe coordination efforts to be successful. There are many systems which satisfy this voice and moderate data rate requirement, seventy-five of which are described by Lomax [Ref. 7: pp. 2-25].

The most prominent communications system used by the government is the public switched network(PSN) which until 1984 had been dominated by the American Telephone and Telegraph Company(AT&T). The PSN also consists of hundreds of smaller regional commercial companies. The federal government satisfies over eighty-five percent of its telecommunications requirements through the use of leased telecommunications from these companies [Ref. 5: p. 4]. In the past, the government has relied heavily upon AT&T to provide the emergency communications planning and preparations necessary to ensure continuity of government during emergencies.

Since the divestiture of AT&T in 1984, the planning requirements on the NCS have dramatically increased. The NCS now must provide the planning for emergency communications and ensure the availability, reliability, capability, compatibility, interoperability, and survivability of its

communications assets. This thesis will develop a measure of survivability which may be used to measure the survivability of different networks.

B. PREVIOUS SURVIVABILITY MODELS

1. TRI-TAC Index of Survivability

The Joint Tactical Communications Office published an analytical study of system effectiveness in 1974 which included survivability as an accountable factor of effectiveness [Ref. 13: pp. 5-7]. In this study sixteen elements of system effectiveness, survivability included, are identified. Each element which is chosen as appropriate to a given system is quantitatively or qualitatively analyzed resulting in a measure of effectiveness(MOE) which is then combined into a figure of merit(FOM). The FOM is then used for a comparative analysis of communication equipment/configuration with respect to system effectiveness.

In reference 13 two MOE's representing survivability are defined: Index of Survivability(overt attack) and index of survivability(jamming). This review will only discuss the index of survivability(overt attack)(SUR_o). The definition of SUR_o is "the ratio of the average number of calls per unit time completed after damage to the average number of calls completed before damage, when the traffic demand is specified and held constant before and after attack"

[Ref. 13: p. 61]. This definition may be represented as:

$$SUR_o = 1 - GOS_{si} / 1 - GOS_i \qquad \text{(eqn 2.1)}$$

where,

GOS_i = Average link grade of service before attack

GOS_{si} = Average link grade of service after attack

The use of equation 2.1 requires four conditions of evaluation to be stated:

1. The call attempts are made during the peak hour.
2. The type of call is specified.
3. If the called subscriber's line is busy, blockage has not occurred.
4. No partial damage to equipment is allowed. The equipment either works or doesn't.

This MOE assesses the ability of communication systems to operate after damage. To calculate SUR_o using equation 2.1 requires evaluating the grade of service both before and after damage. This calculation is discussed next.

a. Grade of Service

Grade of Service(GOS) is the probability that a request for communication service will be blocked [Ref. 13: p. 39]. It is computed as a weighted average of blocking probabilities over all user pairs in a network. The weights are assigned through use of qualitative analysis of selected characteristics of traffic needs for each user pair. The

defining equation may be written as:

$$GOS_i = f(T,C,R,A,D) \qquad \text{(eqn 2.2)}$$

where,

GOS_i = Grade of service of the i^{th} needline.

T = Traffic volume by type of service

R = Alternative routing capability

A = Call or message arrival probability distribution (assumed to be Poisson)

D = Call or message duration

Equation 2.2 may be used as a circuit/network sizing parameter which evaluates capacity required to handle estimated traffic loads.

A quantitative expression for the grade of service if the probability of blocking is considered to be the ratio of blocked calls to the total offered traffic is:

$$GOS_j = \sum e_i \, GOS_i \,/\, \sum e_i \qquad \text{(eqn 2.3)}$$

where,

GOS_j = the network(j)grade of service

GOS_i = the grade of service of the i^{th} needline

e_i = the traffic offered to the i^{th} needline.

This MOE may also be used as a measure of system effectiveness and would be calculated for each type of service listed in Ref. 13, page 40.

2. LaPatra: Measure of Survivability

LaPatra [Ref. 4] developed a "first generation" model of an index of survivability which uses a linear additive parametric equation. His work substantially improves upon that in reference 13 .

The index of survivability(IS) is defined as "the ratio of the network quality factor(NQF), computed after damage, to the NQF computed before damage, when the traffic demand is specified and held constant before and after attack [Ref. 4: p. 3].

$$IS = N_{is} / D_{is} \qquad \text{(eqn 2.4)}$$

where,

D_{is} = Network quality factor before damage

N_{is} = Network quality factor after damage

The NQF is identified to be of the linear additive form:

$$D_{is} = a_1x_1 + a_2x_2 + \ldots + a_kx_k \qquad \text{(eqn 2.5)}$$

$$N_{is} = b_1x_1 + b_2x_2 + \ldots + b_kx_k \qquad \text{(eqn 2.6)}$$

where,

x = identified network parameters

b = before damage weighting factors

a = after damage weighting factors

and IS ≤ 1 and will equal unity under the conditions of no damage.

The parameters$(x_1,...,x_k)$ identified as appropriate for the evaluation of the survivability of a communication network were:

1. Number of nodes = N

2. Average degree of connectivity of nodes = R

3. Link capacity = C

4. Number of links = L

These parameters are scaled to reflect their relative importance by the coefficients(a and b). The values of the coefficients were established by a Delphi technique and would be network dependent. The parameters and coefficients are combined into a linear additive expression(equations 2.5,2.6) and used to determine the IS.

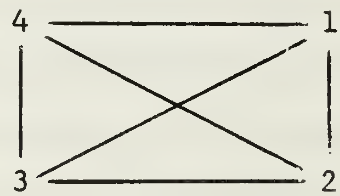
C. METHODOLOGY

To begin a study of survivability, one must define the term survivability. What is meant by survivability? Does this mean the existence of overall system capacity? The maximization of connections within the network? The maintenance of a minimum grade of service?

Survivability of a telecommunications network in the most basic terms is defined as the existence of connectivity between any two nodes within the network. This definition inplies that a node without a communications connection to any other node within the network ceases to exist and provides no useful capability to the network. Connectivity means that at least one communications route is provided from a node to every other node in the network.

In this study, the most survivable group of connections between two nodes is considered to be the maximum independent parallel paths. Independent parallel paths require that a link between two nodes may only be used once in determining the number of parallel paths between a source and a destination node. This is considered to be the most survivable group of connections since with N independent parallel paths the loss of any one link will only result in a loss of 1 connection(or 1/N of the total connections). An example should suffice to show the formulation of independent paths until a more comprehensive discussion later. In Figure 2.1 a fully connected four node network is shown. There are a maximum of three independent parallel paths between the node pair (1,4) as can easily be determined through inspection. As can be seen no link is used more than once in the determination of all the independent paths. Thus the destruction of any one link will only destroy one

path. As the complexity of the network increases the determination of the paths becomes virtually impossible by inspection and a method will need to be developed.



Independent Parallel Paths
For Node Pair (1,4)

1,4
1,3,4
1,2,4

Figure 2.1 Example.

If in Figure 2.1 each link is considered to have a different data capacity then a problem may exist as to how to determine the possible parallel connections which would permit the maximization of the survivable paths and the maximization of the surviving capacity. In an attempt to maximize the capacity of the most survivable connections in a network the following methodology will be used:

1. Review the methodology for determining the connectivity of a fully connected network.

2. Develop an method for determining the connectivity between any two node pairs in an incomplete network.

3. Determine the maximum number of independent parallel paths between any node pair.

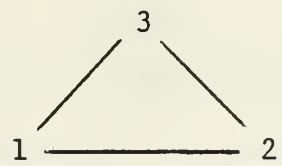
4. Maximize the capacity of the independent parallel paths.

III. PATH ANALYSIS

The development of unique paths performed in this chapter are made assuming source and destination nodes are given. This analysis might be useful for a network which has a priority mission of providing connectivity between two nodes and the secondary mission of providing connectivity for other nodes in the network.

A. CONNECTIVITY OF THE FULLY CONNECTED NETWORK

To establish the necessary background for the analysis of incomplete networks a brief review of fully connected network analysis performed by Pierson [Ref. 14] will be made. For the path analysis performed the lowest numbered node is considered the source and the highest numbered node the destination. This convention will be used throughout the remaining part of this thesis. Figure 3.1 and 3.2 show the number of unique paths for a three and five node network respectively. A unique path is defined as "a path that consists of a unique set and sequence of nodes" [Ref. 14: p. 32]. In a fully connected network consisting of 5 nodes the paths 12345 and 12435 are considered unique from origin 1 and destination 5. The formulation of the solution set of unique paths is based on combinational analysis of the internal nodes(the nodes which are not the source or destination node).



Total number of unique paths between 1 and 3 = 2

1 TWO-node path is : 13

1 THREE-node path is: 123

Total paths = 2

Figure 3.1 Total Connectivity for Three Nodes.

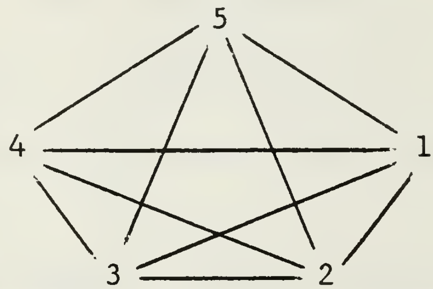
Upon examination of the fully connected networks an equation was developed which may be used to determine the total number of unique paths of a fully connected network given the number of nodes in the network(equation 3.1).

$$U = {}_{n-2}P_{n-2} + {}_{n-2}P_{n-3} + \cdots + {}_{n-2}P_{0} \qquad \text{(eqn 3.1)}$$

where,

N = total number of nodes in the network

U = total number of unique paths in a totally connected network



Total number of unique paths between 1 and 5 = 16

1 TWO-node path is : 15

3 THREE-node paths are: 125/135/145

6 FOUR-node paths are: 1235/1245/1325/1345/1425/1435

6 FIVE-node paths are: 12345/12435/13245/13425/14235/
14325

Total Paths = 16

Figure 3.2 Total Connectivity for Five Nodes.

This equation recognizes that given a source and destination the number of unique paths in a "N" node network is equal to the number of permutations of N-2 nodes taken N-2 at a time plus the number of permutations of N-2 nodes taken n-3 at a time and so on until N-2 nodes taken N-N at a time. This equation may then easily be used to construct a table showing the number of unique paths in any fully connected network. An example is shown in Table I.

TABLE I

UNIQUE PATHS FOR COMPLETE CONNECTIVITY

Nodes	Number of Paths Via "x" nodes					
	x==> 2	3	4	5	6	Total
2	1	-	-	-	-	1
3	1	1	-	-	-	2
4	1	2	2	-	-	5
5	1	3	6	6	-	16
6	1	4	12	24	24	65

B. CONNECTIVITY OF THE INCOMPLETE NETWORK

The determination of the number of unique paths in an incomplete network is much more difficult than that for the complete network. This section will examine incomplete networks and define an method for determining the unique paths in the incomplete networks.

1. Assumptions and Constraints

There are certain assumptions which must be made before the formulations of unique paths may commence. These are made to allow the scope of this study to be kept at a manageable level.

1. No node may be the origin and end of one element, ie. no self loops may exist.

2. No parallel elements connecting the same two nodes may exist.

3. Paths may pass through a node only once.

An incomplete network is considered to be a network in which each node is not directly connected to every other node. This means there are at least two nodes which do not have a direct element between them.[1] In a network with N nodes equation 3.2 can be used to determine whether an incomplete network exists. If the number of links present are less than L then an incomplete network exists.

$$L = N(N-1) / 2 \qquad \text{(eqn 3.2)}$$

where,

L = number of links in a fully connected network

N = number of nodes in the network

To begin path formulation of the incomplete network, elements of the network are grouped into three classifications referenced to their geometric relationship to the source and destination nodes (x,y) [Ref. 15: p. 116]. In this study the source node x will always be labeled 1 and the destination node y will be labeled with the highest node number in the network. The three element classifications are:

---

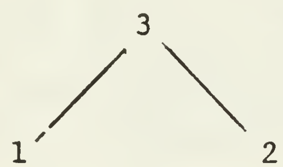
[1] The terms element and link are used synonymously throughout the remainder of this thesis.

1. Class A: an element which is connected between the source and destination nodes (x,y).

2. Class B: an element which has one end connected to either node x or y. The other end is not connected to either x or y.

3. Class C: an element which is not connected to either node x or y.

The analysis will be performed on networks with only one link missing, then more complicated network omissions will be analyzed.



Total number of unique paths between 1 and 3 = 1

0 TWO-node path

1 THREE-node path is: 123

Total paths = 1

Figure 3.3 Three Node Class A Network.

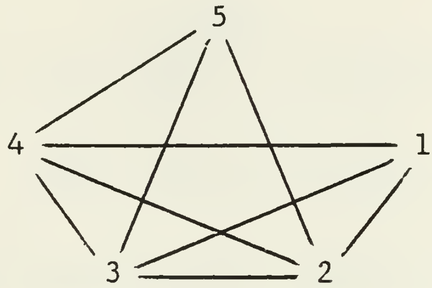
2. Class A Network Path Formulation

Path analysis of networks involving the loss of only a class A element are simple and trivial at best. Since a

class A link is connected to the source and destination nodes there is one and only one link in any complete network which may be considered class A. Therefore the loss of a class A link will only result in the loss of one link from the fully connected network. Figures 3.3 and 3.4 show the networks which correspond with Figures 3.1 and 3.2 except with the class A link missing. Table II shows the connection paths for networks of node size 2 through 6.

3. Class B Network Path Formulation

Class B networks are those networks with a class B element missing. That is a link which has one end connected to either the source or destination node and the other end in not connected to either x or y. The formulation of unique paths for this class will be carried out by inspection using networks up to six nodes then establishing mathematical formulas for use. To calculate the unique paths for a class B network an examination of the fully connected networks unique paths solution set is made and any path with the omitted link as the first or last element is rejected. The remaining paths are the solution set for the class B network. It is not possible to have one class B element missing from a network with only two nodes. Figures 3.5 through 3.8 show the class B networks for networks with three to six nodes. These figures are self explanatory.



Total number of unique paths between 1 and 5 = 15

0 TWO-node path

3 THREE-node paths are: 125/135/145

6 FOUR-node paths are: 1235/1245/1325/1345/1425/1435

6 FIVE-node paths are: 12345/12435/13245/13425/14235/14325

Total paths = 16

Figure 3.4 Five Node Class A Network.

By examining the solution sets to the fully connected networks [Ref. 14: pp. 34-37] and eliminating the paths with the missing element as the first element, the solution set for the incomplete networks are formed. Table III shows the fully connected network paths eliminated due to the omission of the class B element(link 12) in networks from three to six nodes.

TABLE II

CONNECTIVITY OF THE CLASS A NETWORK

Nodes	Number of paths via "x" nodes x==> 2	3	4	5	6	Total
2	-	-	-	-	-	0
3	-	1	-	-	-	1
4	-	2	2	-	-	4
5	-	3	6	6	-	15
6	-	4	12	24	24	64

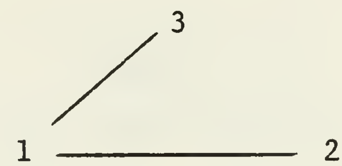
Reference 15 gives an equation for determining the number of unique paths in a class B network as:

$$(1-1/N-2)({}_{N-2}P_{N-2} + {}_{N-2}P_{N-3} + \cdots + {}_{N-2}P_{1}) + {}_{N-2}P_{0}. \quad \text{(eqn 3.3)}$$

Using figures, 3.5, 3.6, 3.7, 3.8, and equation 3.3, Table IV is constructed to show the number of unique paths in class B networks up to eight nodes.

4. <u>Class C Network Path Formulation</u>

Class C networks are considered to be those incomplete networks with one class C element missing. A class C link is one which is connected to neither the source or the



Total number of unique paths between 1 and 3 = 1

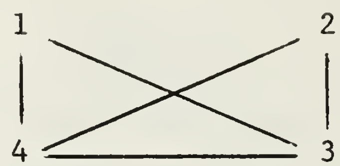
1 TWO-node path: 13

0 THREE-node paths

Total paths = 1

Figure 3.5   Three Node Class B Network.

destination node. The formulation of the unique paths solution set for the class C network will be completed by inspection of the fully connected network path set and elimination of those paths which contain the omitted element. The solution set must reject any path with the element nodes listed consecutively without regard to order. It should be noted that a class C network requires a minimum of four nodes to allow the omission of an element not connected to an external node(source or destination node). Table V shows the paths which are rejected from the solution set of the fully connected network when determining the class C unique



Total Number of Unique Paths between 1 and 4 = 3

1 TWO-node path: 14

1 THREE-node path: 134

1 FOUR-node path: 1324

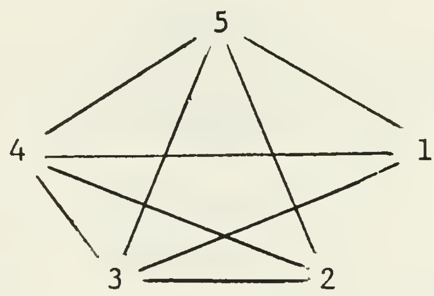
Total paths= 3

Figure 3.6 Four Node Class B Network.

paths solution sets. Examination of table V shows that each rejected path contains the omitted element(23 or 32). Figures 3.9, 3.10, and 3.11 show the solution sets for the class C networks with element 23/32 missing.

5. Multiple Omission of Elements

The omission of multiple elements allows the characterization of any network in use today. The analysis of networks which are characterized by multiple element omissions is performed using the same analysis technique as used in the analysis in the preceding four sections. With the



Total number of unique paths between 1 and 5 = 11

1 TWO-node path: 15

2 THREE-node paths: 135/145

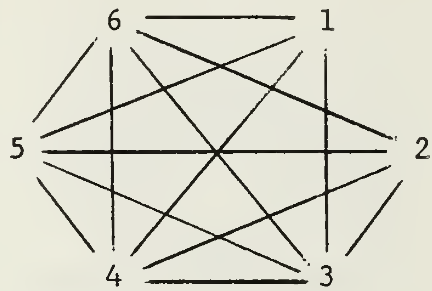
4 FOUR-node paths: 1325/1345/1425/1435

4 FIVE-node paths: 13245/13425/14235/14325

Total Paths = 11

Figure 3.7 Five Node Class B Network.

help of the program discussed in the next section the analysis of the multiple omission networks unique paths is simple. The unique analysis for a five and six node network with multiple omissions are shown in Figures 3.12 and 3.13 The five node network has three elements missing; one class A, one class B, and one class C. The six node network has one class A, two class B, and two class C links missing.



Total number of unique paths between 1 and 6 = 49

1 TWO-node path: 16

3 THREE-node paths: 136/146/156

9 FOUR-node paths: 1326/1346/1356/1426/1436/1456/1526/1536/1546

18 FIVE-node paths: 13246/13256/13426/13456/13526/13546/14236/14256/14326/14356/14526/14536/15236/15246/15326/15346/15426/15436

18 SIX-node paths: 132456/132546/134256/134526/135246/135426/142356/142536/143256/143526/145236/145326/152346/152436/153246/153426/154236/154326

Total Paths = 49

Figure 3.8 Six Node Class B Network.

Note how this analysis may be used for any network topology. Figure 3.13 shows one possible six node topology.

TABLE III

OMITTED PATHS OF CLASS B NETWORK WITH ELEMENT 12 MISSING

FOUR-node network:	124/1234
FIVE-node network:	125/1235/1245/12345/12435
SIX-node network:	126/1236/1246/1256/12346/12356/ 12436/12456/12536/12546/123456/ 123546/124356/124536/125346/125436

TABLE IV

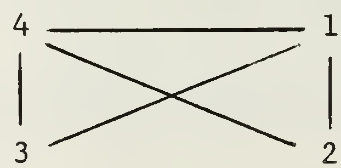
CONNECTIVITY OF THE CLASS B NETWORK

Nodes	Number of paths via "x" nodes							
x=>	2	3	4	5	6	7	8	Total
3	1	-	-	-	-	-	-	1
4	1	1	1	-	-	-	-	3
5	1	2	4	4	-	-	-	11
6	1	3	9	18	18	-	-	49
7	1	4	16	48	96	96	-	261
8	1	5	25	100	300	600	600	1631

TABLE V

OMITTED PATHS OF CLASS C NETWORK WITH ELEMENT 23 MISSING

FOUR-node network	=	1234/1324
FIVE-node network	=	1235/1325/12345/13245/14235/14325
SIX-node network	=	1236/1326/12346/12356/13246/13256/14236/14326/15236/15326/123456/123546/132456/132546/142356/143256/145236/145326/152346/153246/154236/154326

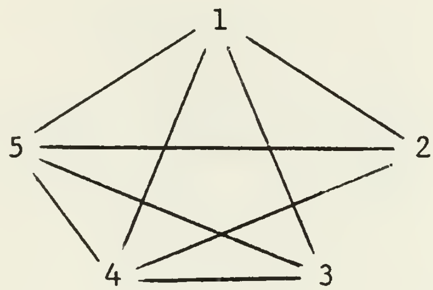


1 TWO-node path: 14

2 THREE-node paths: 124/134

Total paths = 3

Figure 3.9 Four Node Class C Network.



1 TWO-node path: 15

3 THREE-node paths: 125/135/145

4 FOUR-node paths: 1245/1345/1425/1435

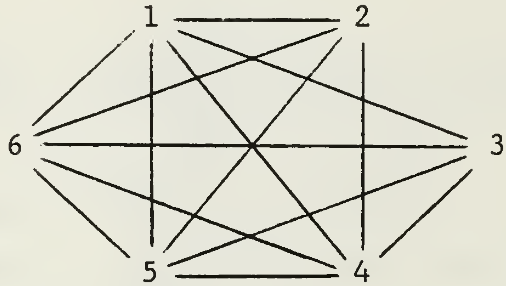
4 FIVE-node paths: 12435/13425

Total paths = 10

Figure 3.10 Five Node Class C Network.

6. <u>Program</u>

The analysis just concluded for finding the unique paths in networks with one element missing was reasonably simple and the paths were easy to determine by inspection. But what if more than one element of each class or more than one class of element were missing in a single network? This would make the problem of finding the unique paths much more complex and a mathematical characterization of the number of



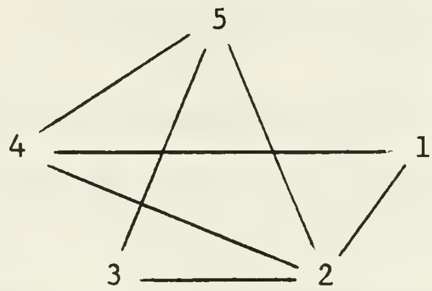
1	TWO-node path:	16
4	THREE-node paths:	126/136/146/156
10	FOUR-node paths:	1246/1256/1346/1356/1456/1546/ 1536/1526/1436/1426
16	FIVE-node paths:	12456/12546/13456/13546/14256/ 14526/14356/14536/15436/15426/ 15346/15246/13426/13526/12436/ 12536
12	SIX-node paths:	124356/124536/125346/125436/ 134526/134256/135426/135246/ 142536/143526/152436/153426

Total paths = 43

Figure 3.11 Six Node Class C Network.

paths would be difficult and out of the intended scope of this thesis.

To determine the unique paths of a network a computer program has been developed by the author and is



2 THREE-node paths: 125/145

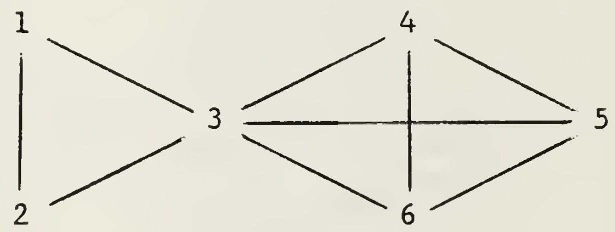
3 FOUR-node paths: 1235/1245/1425

1 FIVE-node path: 14235

Total paths = 6

Figure 3.12 Five Node Multiple Element Omission Network.

included as an Appendix. This program is written in FORTRAN WATFIV and may be used for any network up to and including six nodes in size. This program could easily be expanded to accept networks of much larger size with minimum modifications. The inputs required for the execution of this program are the destination node(nodes must be numbered consecutively from the source node to the destination with the source node as one) and the connectivity between each node in the network. The program will list the number of missing elements by class and then list all unique paths from the source to destination.



1 THREE-node path: 136

3 FOUR-node paths: 1236/1346/1356

4 FIVE-node paths: 12346/12356/13456/13546

2 SIX-node paths: 123456/123546

Total paths = 10

Figure 3.13 Six Node Multiple Element Omission Network.

The program in the Appendix may not be written in the most efficient manner but for the purposes of this thesis it is sufficient. It shows a program listing with the results of a six node network with elements 23/32 and 45/54 missing.

IV. INDEPENDENT PATHS

Survivability, as defined in Chapter 2, is the existence of connectivity between any two nodes in a network. This chapter will develop a method of determining the maximum number of independent paths between a source and destination node of a network. The analysis will use the unique paths developed in Chapter 3. The aim of this development is to show the network manager the most survivable configuration of the network when attempting to connect two priority users. The analysis would be beneficial in the situation where a networks assests are to primarily be used to connect two priority users and any other connectivity provided for other users is of secondary importance.

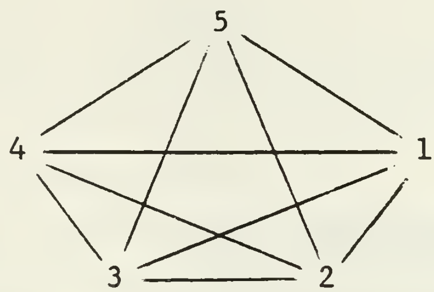
It is fair to say that the more routes available between two nodes the higher degree of survivability, *cetera paribus*. This statement is based on the fact that the loss of any one route will not severe the connectivity if more than one route exists. By using the unique paths of a network, a maximum set of independent paths between a source and destination node is easily found. Independent paths are paths which do not use a common link in the path between a source and destination node, thus the loss of any link will result in the loss of only one path between the nodes. The maximum

number of independent paths between a source and destination node is considered to be the most survivable set of communication paths. This analysis does not take into account redundancy between two nodes, hardness, mobility, ease of reconfiguration, or other methods of increasing survivability. This analysis assumes that four independent paths are better than three because it increases the probability of survival in the case of natural disasters or malicious attack.

A. FULLY CONNECTED NETWORKS

The development of the independent paths in a network begins with a comparison of the unique paths in an attempt to identify the maximum number of independent paths possible. It may easily be seen by examining Figure 3.1 that the number of unique paths for the three node fully connected network are two and the independent paths are also the same. Figure 2.1 shows the independent paths for the four node fully connected network. The maximum number of independent paths in this case were found by eliminating the four node path(1234) since its inclusion would limit the number of independent paths to two. Now an examination of larger networks will begin.

A close look at Figures 3.2, 4.2, and 4.1 will show the reader the method used to determine the maximum number of independent paths. The analysis began by comparing the



Maximum number of independent paths between 1 and 5 = 4

Independent paths are: 15/125/135/145

Figure 4.1 Five Node Network Independent Paths.

minimum node unique path(15) with the other unique paths and if no common link was found to be used the next comparison is made. A point should be made that a two node path may not have a common node with any other path, therefore if a class A element is present in the network it will be a part of the maximum independent path solution set. Therefore the first actual comparison to be made is for element 125. It may be seen that 125 has common elements with eight paths in the unique solution set, therefore these elements may be eliminated from further comparisons. The next path(135) has common elements with four of the remaining paths thus leaving path 145 as the remaining element. This set of

maximum independent paths represent the most survivable set of paths from node 1 to 5 because they provide the most connectivity between the nodes, not accounting for capacity.

1. Maximum Independent Path Solution Set: 15,125

   Paths eliminated: 1235/1245/1325/1425/12345/12435
   13425/14325

2. Maximum Independent Path Solution Set: 15,125,135

   Paths eliminated: 1345/1435/13245/14235

3. Maximum Independent Path Solution Set: 15/125,135,145

Figure 4.2 Five Node Independent Path Analysis.

But this set of independent paths is not the only set which has four independent paths. The nine possible sets of four independent paths are given in Table VI. The discussion of how the paths were found will occur in the next section for the five node class A network. The only difference is the addition of path 15 to each possible set of independent paths. In the next chapter, a discussion of which set of maximum independent paths is the preferred configuration will be addressed.

TABLE VI

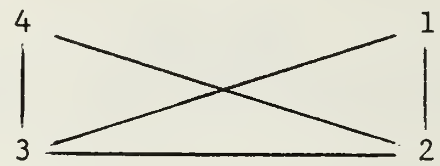
MAXIMUM PATHS FOR FIVE NODE FULLY CONNECTED NETWORK

The maximum independent paths = 4

15/125/135/145	15/125/1345/14235
15/125/1435/13245	15/135/1245/14325
15/135/1425/12345	15/145/1235/13425
15/145/1325/12435	15/1235/1345/1425
15/1245/1325/1435	

B. CLASS A NETWORKS

The elimination of a class A element from the fully connected network reduces the unique solution set by one path as shown in Chapter 3. The affect of this link reduction on the maximum independent path solution set is now to be examined. In the two node network the loss of a class A element will result in no connectivity between the source and destination, thus no independent paths. For the three node network the loss of the class A element will result in only one unique path as seen in Figure 3.3 thus only one independent path is available(path 123). These results are simple to see.



Independent paths: 1234 or 124/134

Maximum independent paths: 124/134

Figure 4.3 Four Node Class A Network.

The loss of a class A link in the four node network results in two possible independent path solution sets (1234 and 124/134) as shown in Figure 4.3. The maximum independent path solution is 124/134 since it provides two independent paths between node 1 and 4. In this case there was a unique maximum independent path solution set but in the case of the five node network to follow this will not be true.

The five node network unique paths are shown in Figure 3.4. The analysis of this network, as shown in Figure 4.4, will proceed using the same method as used for the fully connected five node network earlier in this chapter. The first comparison is for path 125 which finds 8 paths eliminated. The second comparison with the remaining paths uses path 135 and shows 4 more paths eliminated leaving 145 to be

1. Maximum solution set: 125

Paths eliminated: 12345/12435/13425/14325
1235/1245/1325/1425

2. Maximum solution set: 125/135

Paths eliminated: 13245/14235/1345/1435

3. Maximum independent paths: 125/135/145

Figure 4.4 Five Node Class A Network Analysis.

added to the solution set(125,135,145). But is this a unique maximum independent paths solution? The answer to this question is no and the logic for this answer will now be shown.

Instead of selecting the first comparison to be made using path 125 let path 1235 be chosen. The first comparison of path 1235 shows 11 paths are eliminated with paths 145/1345/1425/13425 remaining. The second comparison using path 145 eliminates two paths leaving the solution set as 1235/145/13425. What if the second comparison would have been completed using 1345 instead of 145? This comparison would have eliminated paths 145/13425 leaving the solution set as 1235/1345/1425. Thus it has been shown that there is no unique maximum independent path solution set for the five node class A network. How many possible solutions are there

with three independent paths? There are nine possible three path solution sets as shown in Table VII.

A computer program for determining the combinations of the maximum number of independent paths could be developed to make this analysis more efficient and to allow analysis of networks larger than five nodes. Without a program, the analysis becomes unmanageable for large networks.

TABLE VII

MAXIMUM PATHS FOR FIVE NODE CLASS A NETWORK

The maximum independent paths = 3

125/135/145	125/1345/14235
125/1435/13245	135/1245/14325
135/1425/12345	145/1235/13425
145/1325/12435	1235/1345/1425
1245/1325/1435	

C. CLASS B NETWORKS

The analysis of the independent paths for the class B networks will proceed using the same methodology used in the previous two sections. Class B networks are those networks missing one element which has one end connected to the source or destination and the other end not connected to the

source or destination. By examining Figure 3.5 it is seen that the loss of a class B element results in only one unique path thus only one independent path for the three node network. The four node network of figure 3.6 shows that there are two possible independent path solutions with two paths, 14/134 and 14/1324. These are the only two solution sets.

The five node class B network is shown in Figure 3.7. To be noted before the analysis begins is that by examining the source and destination nodes one may immediately determine the maximum number of independent paths. This may be done by determining the minimum number of links ending at either the source or destination node, in this case three at the source. Therefore three independent paths will exist in this network. This will not be accurate once multiple class omissions are allowed but this method could be used to get a quick look maximum. The complete analysis is shown in Figure 4.5 and begins by selecting the first comparison object 135 and eliminating all paths with common elements. The remaining paths can therefore be constructed into a solution set since the maximum number of independent paths are known to be three. After the first solution set only the paths which have not already been included in the

1. Solution set: 15/135

Paths eliminated: 1325/1345/1435/13245/13425/14235

Paths remaining: 145/1425/14325

2. Solution set: 15/145

Paths eliminated: 1345/1425/1435/13245/14235/14325

Paths remaining: 135/1325/13425

3. Solution set: 15/1325

Paths eliminated: 135/1345/1425/13245/13425/14235/14325

Paths remaining: 145/1435

4. Solution set: 15/1345

Paths eliminated: 135/145/1325/1435/13245/13425/14325

Paths remaining: 1425/14235

5. Solution set: 15/1425

Paths eliminated: 145/1325/1435/13425/14235/14325

Paths remaining: 135/1345/13245

Maximum Solution Set:

15/135/145	15/135/1425	15/135/14325
15/145/1325	15/145/13425	15/1325/1435
15/1345/1425	15/1345/14235	15/1425/13245

Figure 4.5 Five Node Class B Analysis.

maximum solution set are added. This is repeated for each possible solution set and then the solution sets are

combined into the set of maximum number of independent paths.

D. CLASS C NETWORKS

Class C networks are those networks missing one element which does not terminate at either the source or destination node. The analysis of the class C network is completed using the same methodology as that previously used. By inspection the four node class C network shown in Figure 3.9 can easily be seen to have a unique maximum independent path solution set of 14/124/134. This solution is not surprising since the loss of element 23 only eliminated the four node paths.

The analysis of the five node class C network depicted in Figure 3.10 is shown in Figure 4.6. This analysis finds the maximum set of independent paths is four and there is a unique solution set. The five node analysis shown could be carried out to show all the possible combinations and confirm that no other four path solution set exists. The analysis of the six node class C network would show no unique solution set.

E. MULTIPLE OMISSION NETWORKS

The independent path analysis for all possible networks with multiple element missing would be too lengthy and therefore the five and six node networks of Figures 3.12 and

1. Solution set: 15/125/135/

Paths eliminated: 1245/1345/1435/1425/12435/13425

Paths remaining: 145

2. Solution set: 15/125/1345

Paths eliminated: 135/145/1245/1425/1435/12435/13425

Paths remaining:

3. Solution set: 15/125/1435

Paths eliminated: 135/145/1245/1345/1425/12435/13425

Paths remaining:

4. Solution set: 15/135/1245

Paths eliminated: 125/145/1345/1425/1435/12435/13425

Paths remaining:

5. Solution set: 15/1245/1435

Paths eliminated: 125/135/145/1345/1425/12435/13425

Paths remaining:

Maximum Solution Set:

15/125/135/145

Figure 4.6 Five Node Class C Analysis.

3.13 will be analyzed as representative. The five node network has an independent path maximum of 2. This was determined by examining the source and destination node and

TABLE VIII

FIVE NODE MULTIPLE OMISSION ANALYSIS

Maximum independent path solution set:

125/145	125/14235
145/1235	1235/1425

seeing that only two links originate at the source, therefore the absolute maximum number of independent paths is two. The solution of the four possible sets of independent paths are shown in Table VIII. The results of the six node network are shown in Table IX. Like the five node network above, the solution set consists of two independent paths. A look at the figure shows that all connectivity between node 1 and 6 must pass through node 3. Since only two links leave node 1, this would be the maximum.

TABLE IX

SIX NODE MULTIPLE OMISSION ANALYSIS

Maximum independent path solution set:

136/12346	136/12356	136/123456
136/123546	1236/1346	1236/1356
1236/13456	1236/13546	1346/12356
1356/12346		

V. PREFERRED SOLUTION CHOICE PROBLEM

The analysis of the independent paths in Chapter 4 shows that many, if not most, networks will have multiple maximum independent paths. The question now is which of the maximum independent paths in the solution set is the preferred configuration for the network? This question allows the network manager to choose a method of deciding which configuration is the best. In this analysis the differentiation of the possible paths will be based on the capacity of the links. If the capacity of the links are uniform throughout the network then another decision variable would be necessary for the differentiation. In the case of a natural disaster or malicious attack, the manager of an emergency communications system may be required to construct a network from the remnants of various other networks with non-uniform capacities. The objective of the network manager would be to maximize the capacity of the paths between the source and destination. This could be accomplished by choosing the path set with the most uniform capacities in each path. A detailed discussion of this decision problem is to follow.

For this analysis, an evaluation of the five node network of Figure 3.12 will be completed. Figure 3.12 shows the five node network and gives all of the unique paths for

TABLE X

CAPACITIES OF A FIVE NODE NETWORK

link	capacity(Kbps)	link	capacity(kbps)
12	4.8	14	64.0
23	9.6	24	1544.0
25	64.0	35	64.0
45	9.6		

this network. The analysis of the independent paths occurred in Chapter 4 and the four possible independent path solutions are shown in Table VIII. Now assume that the links in this network have the capacities listed in Table X. By tracing each set of independent paths through and determining the capacity of that path the results in Table XI are achieved.

The maximum capacity of a path may only be as high as the link with the minimum capacity in that path. In evaluating path 125 the link capacities may be seen to be 4.8 and 64.0 Kbps, therefore the path capacity is 4.8 Kbps. The completed analysis in Table XI shows that the maximum capacity configuration of the most survivable connections in this network would be 1235/1425. Note that there would be

TABLE XI

CAPACITY CHOICE OF A FIVE NODE NETWORK

Paths	Capacities
125/145	4.8/9.6
125/14235	4.8/9.6
145/1235	9.6/4.8
1235/1425	4.8/64.0

no preference of the other three sets of paths with respect to capacity. If the last set of independent paths were not available then another decision variable would have to be chosen. In this case, the manager may decide to pick the first configuration since it has the minimum number of paths and is thus less susceptible to damage.

A second analysis may be worthwhile to complete. The six node network in Figure 3.13 and the independent path analysis of Table IX are analyzed using the capacities listed in Table XII. The analysis in Table XIII shows that the network manager may choose any of five network configurations and still be able to maintain a capacity of 9.6 and 64.0 Kbps on the two independent paths. Thus another decision variable would need to be chosen to differentiate the five configurations.

TABLE XII

CAPACITIES FOR A SIX NODE NETWORK

Path	Capacity(Kbps)	Path	Capacity(Kbps)
12	128.0	13	9.6
23	64.0	34	9.6
35	1544.0	36	64.0
45	128.0	46	9.6
56	128.0		

TABLE XIII

CAPACITY CHOICE OF A SIX NODE NETWORK

Paths	Capacities	Paths	Capacities
136/12346	9.6/9.6	136/12356	9.6/64.0
136/123456	9.6/9.6	136/123546	9.6/9.6
1236/1346	64.0/9.6	1236/1356	64.0/9.6
1236/13456	64.0/9.6	1236/13546	64.0/9.6
1346/12356	9.6/9.6	1356/12346	9.6/9.6

The capacity choice problem is just one of many choice problems which may be used to differentiate between the independent paths. This problem allows the manager to use discretion in his choice of network configuration.

VI. CONCLUSION

The analysis of networks has been systematically completed to develop a possible decision aid for the network manager in an effort to maximize the capacity of a networks most survivable connection paths. The method developed for this analysis was to develop the set of all unique paths between the source and destination then restrict that set of paths to allow only the independent paths(those with no common links) to remain in the solution set. The most survivable network configuration was considered to be the set of maximum number independent paths. It was found that many networks do not have a unique set of maximum independent paths, therefore the path capacities were used as a decision variable to differentiate between the path sets.

The analysis has not accounted for the multitude of methods for increasing survivability. The survivability of the network may be characterized as (1 - 1/number of independent paths). This relationship shows the affects of the loss of one independent path on the system. The analysis attempted to account for the multiple use of one link but did not restrict the independent paths from using the same nodes. This restriction could lead to an area of further research. Another area of research would be to design a

computer program to accomplish the analysis which could be used in a dynamic situation to configure the network.

APPENDIX

UNIQUE PATH PROGRAM AND LISTING

```
$JOB WATFIV
C THIS PROGRAM IS DESIGNED TO FIND THE UNIQUE PATHS IN A NETWORK
C UP TO SIX NODES.
C DEFINE VARIABLES
      INTEGER DEST,I,J,K,L,M,N,P,COUNT,X,Y
      INTEGER S(7,7)
C ENTER DESTINATION NODE
      PRINT, 'PLEASE, ENTER DESTINATION NODE, NOTE NODES MUST BE LABEL-'
      PRINT, 'ED CONSECUTIVELY FROM SOURCE NODE(=1) TO DESTINATION NODE'
      READ,DEST
C ENTER CONNECTION DATA
      DO 30 I=1,DEST,1
        DO 20 J=1,DEST,1
          IF (I.NE.J) THEN
           PRINT,'ENTER VALUE FOR ELEMENT',I,J
           PRINT,'1 = CONNECTED, 0 = NOT CONNECTED'
           READ,S(I,J)
           PRINT 5,I,J,S(I,J)
5      FORMAT(T1,'0','S(',I1,',',I1,') = ',I1)
          ELSE
           S(I,J)=0
          END IF
20      CONTINUE
30    CONTINUE
C LIST THE NUMBER OF CLASS A, B, AND C ELEMENTS MISSING
      IF (S(1,DEST).EQ.0) THEN
        PRINT,1,' CLASS A ELEMENT MISSING'
      ELSE
        PRINT,0,' CLASS A ELEMENT MISSING'
      END IF
      X=0
      Y=DEST-1
```

```
      DO 52 J=2,Y,1
        IF (S(1,J).EQ.0) THEN
          X=X+1
        END IF
52    CONTINUE
      DO 55 I=2,DEST,1
        IF (S(I,DEST).EQ.0) THEN
          X=X+1
        END IF
55    CONTINUE
      PRINT,X/2,' CLASS B ELEMENTS MISSING'
      COUNT=0
      DO 57 I=2,Y,1
        DO 56 J=2,Y,1
          IF (S(I,J).EQ.0.AND.I.NE.J) THEN
            COUNT=COUNT+1
          END IF
56    CONTINUE
57    CONTINUE
      PRINT,COUNT/2,' CLASS C ELEMENTS MISSING'
C NOW DETERMINE THE UNIQUE PATHS IN THE NETWORK.
C START AT THE SOURCE AND DETERMINE ALL THE PERMUTATIONS TO THE DESTINATION
      P=0
      DO 90 J=2,DEST,1
        IF (J.EQ.DEST.AND.S(1,J).EQ.1) THEN
          PRINT,1,J
          P=P+1
        ELSEIF (S(1,J).EQ.1) THEN
1         DO 80 K=2,DEST,1
            IF (K.EQ.DEST.AND.S(J,K).EQ.1) THEN
              PRINT,1,J,K
              P=P+1
            ELSEIF (J.NE.K.AND.S(J,K).EQ.1) THEN
              DO 70 L=2,DEST,1
                IF(L.EQ.DEST.AND.S(K,L).EQ.1) THEN
                  P=P+1
                  PRINT,1,J,K,L
```

```
                    ELSEIF (K.NE.L.AND.S(K,L).EQ.1.AND.J.NE.L) THEN
                      IF (DEST.EQ.L) THEN
                        PRINT,1,J,K,L
                        P=P+1
                      END IF
                      DO 60 M=2,DEST,1
                        IF(M.EQ.DEST.AND.S(L,M).EQ.1) THEN
                        PRINT,1,J,K,L,M
                        P=P+1
                  ELSEIF (M.NE.L.AND.S(L,M).EQ.1.AND.M.NE.K.AND
     *            .M.NE.J) THEN
                          IF (DEST.EQ.M) THEN
                            PRINT,1,J,K,L,M
                            P=P+1
                          END IF
                          DO 50 N=2,DEST,1
                            IF (N.EQ.DEST.AND.S(M,N).EQ.1) THEN
                              PRINT,1,J,K,L,M,N
                              P=P+1
                            ELSEIF (N.NE.M.AND.N.NE.L.AND.N.NE.K.AND.
     *                      N.NE.J.AND.S(M,N).EQ.1)THEN
                              PRINT,1,J,K,L,M,N
                              P=P+1
C THIS PROGRAM MAY BE EXPANDED EASILY TO ACCOMMODATE NETWORKS OF LARGER
C THAN SIX NODES BY SIMPLY ADDING MORE DO AND IF STATEMENTS SUCH AS THE
C ONES ABOVE
                            END IF
   50                     CONTINUE
                        END IF
   60                 CONTINUE
                    END IF
   70             CONTINUE
                END IF
   80         CONTINUE
            END IF
   90     CONTINUE
          PRINT 100,P
```

```
  100   FORMAT(T1,'0',T2,I4,' UNIQUE PATHS')
        STOP
        END
0          $ENTRY
 PLEASE, ENTER DESTINATION NODE, NOTE NODES MUST BE LABEL-
 ED CONSECUTIVELY FROM SOURCE NODE(=1) TO DESTINATION NODE
 ENTER VALUE FOR ELEMENT            1            2
 1 = CONNECTED, 0 = NOT CONNECTED
0S(1,2) = 1
 ENTER VALUE FOR ELEMENT            1            3
 1 = CONNECTED, 0 = NOT CONNECTED
1S(1,3) = 1
 ENTER VALUE FOR ELEMENT            1            4
 1 = CONNECTED, 0 = NOT CONNECTED
0S(1,4) = 1
 ENTER VALUE FOR ELEMENT            1            5
 1 = CONNECTED, 0 = NOT CONNECTED
0S(1,5) = 1
 ENTER VALUE FOR ELEMENT            2            1
 1 = CONNECTED, 0 = NOT CONNECTED
0S(2,1) = 1
 ENTER VALUE FOR ELEMENT            2            3
 1 = CONNECTED, 0 = NOT CONNECTED
0S(2,3) = 0
 ENTER VALUE FOR ELEMENT            2            4
 1 = CONNECTED, 0 = NOT CONNECTED
0S(2,4) = 1
 ENTER VALUE FOR ELEMENT            2            5
 1 = CONNECTED, 0 = NOT CONNECTED
0S(2,5) = 1
 ENTER VALUE FOR ELEMENT            3            1
 1 = CONNECTED, 0 = NOT CONNECTED
0S(3,1) = 1
 ENTER VALUE FOR ELEMENT            3            2
 1 = CONNECTED, 0 = NOT CONNECTED
0S(3,2) = 0
 ENTER VALUE FOR ELEMENT            3            4
```

```
 1 = CONNECTED, 0 = NOT CONNECTED
OS(3,4) = 1
 ENTER VALUE FOR ELEMENT          3             5
 1 = CONNECTED, 0 = NOT CONNECTED
OS(3,5) = 1
 ENTER VALUE FOR ELEMENT          4             1
 1 = CONNECTED, 0 = NOT CONNECTED
OS(4,1) = 1
 ENTER VALUE FOR ELEMENT          4             2
 1 = CONNECTED, 0 = NOT CONNECTED
OS(4,2) = 1
 ENTER VALUE FOR ELEMENT          4             3
 1 = CONNECTED, 0 = NOT CONNECTED
OS(4,3) = 1
 ENTER VALUE FOR ELEMENT          4             5
 1 = CONNECTED, 0 = NOT CONNECTED
OS(4,5) = 0
 ENTER VALUE FOR ELEMENT          5             1
 1 = CONNECTED, 0 = NOT CONNECTED
1S(5,1) = 1
 ENTER VALUE FOR ELEMENT          5             2
 1 = CONNECTED, 0 = NOT CONNECTED
OS(5,2) = 1
 ENTER VALUE FOR ELEMENT          5             3
 1 = CONNECTED, 0 = NOT CONNECTED
OS(5,3) = 1
 ENTER VALUE FOR ELEMENT          5             4
 1 = CONNECTED, 0 = NOT CONNECTED
OS(5,4) = 0
             0  CLASS A ELEMENT MISSING
             1  CLASS B ELEMENTS MISSING
             1  CLASS C ELEMENTS MISSING
             1            2            4             3             5
             1            2            5
             1            3            4             2             5
             1            3            5
             1            4            2             5
```

```
                1           4           3           5
                1           5
     0   7 UNIQUE PATHS
```

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